



# Overview of Propagation Studies at NASA Glenn Research Center

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Advanced High Frequency Branch



*Keeping the universe connected.*

January 22, 2015

- Propagation Program Objectives
- Program History
- Summary of Current Propagation Campaigns
- Modeling Activities
- GRC Propagation Laboratories
- Future Plans

# Program Objectives



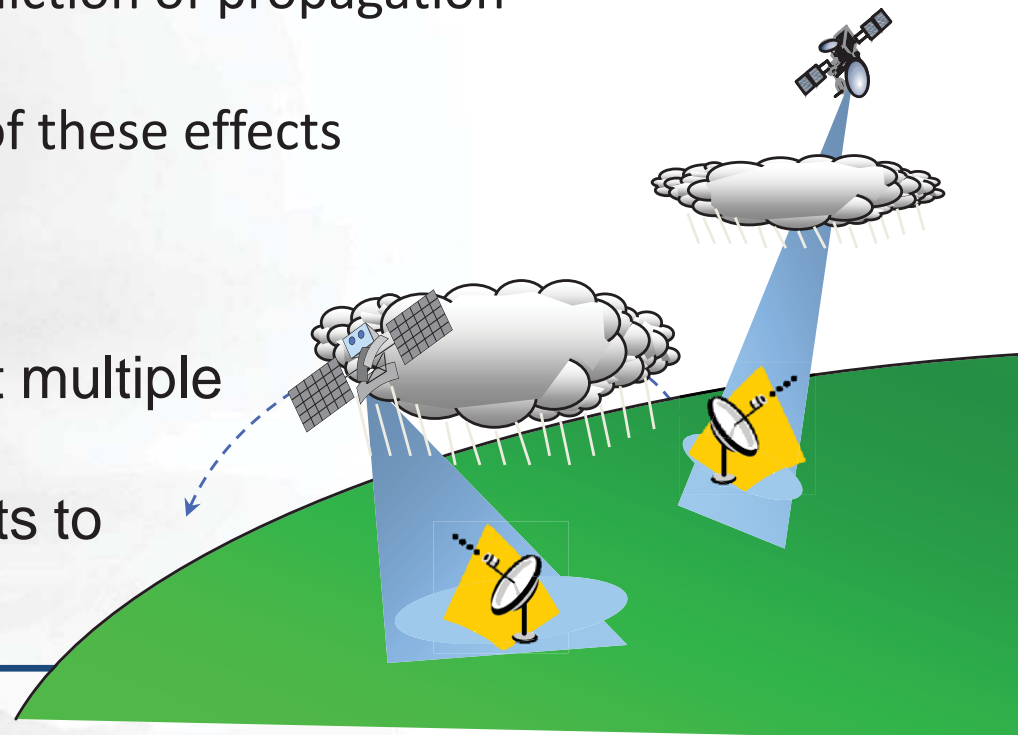
*As NASA and the Nation move toward operations at Ka-band frequencies and above, it is desirable to characterize the site-dependent atmospheric propagation effects to manage expectations for system performance and develop improved systems at current and future potential operational sites.*

## Objectives:

- To provide a good understanding of RF propagation effects
- To develop or validate models for the prediction of propagation-related effects
- To develop techniques for the mitigation of these effects

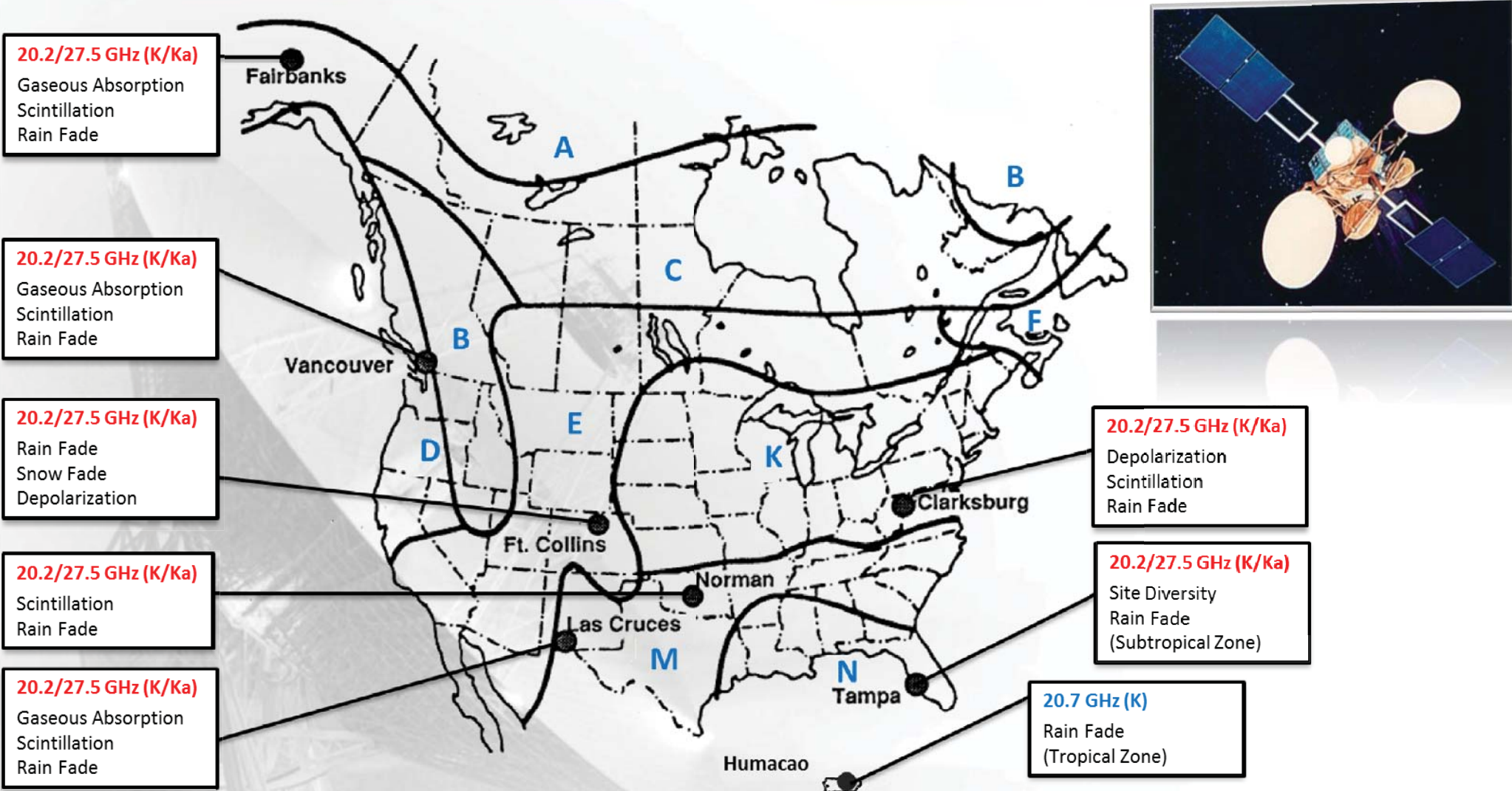
## How to accomplish the objectives:

- By making long-term measurements at multiple sites and analyzing the collected data
- A timely and full dissemination of results to users of propagation data



# Program History

## Advanced Component Technology Satellite (ACTS)



GRC possesses over 35+ station years of Ka-band propagation data collected through the Advanced Communications Technology Satellite (ACTS) program.



# Overview of Current Efforts





# Propagation Terminal Development



ACTS Propagation Terminal

Operational Frequency: 20.7/27.5 GHz

**Dynamic Range: 20 dB**

Sampling Rate: 1 Hz/10 Hz

**Resolution: <0.3 dB rms accuracy**

**Hardware-based FFT Receiver**



Goldstone Interferometer

Operational Frequency: 20.2 GHz

**Dynamic Range: 30 dB**

Sampling Rate: 1 Hz

**Resolution: <0.1 dB rms accuracy**

**Software-based FFT Receiver**



White Sands/Guam Terminal

Operational Frequency: 20.2 GHz

**Dynamic Range: 40 dB**

Sampling Rate: 1 Hz/10 Hz

**Resolution: <0.1 dB rms accuracy**

**Software-based Frequency Estimation Receiver**

Throughout propagation campaigns, ground station hardware has undergone evolutionary improvements in performance and autonomous operation procedures.

A large, white, parabolic radio telescope dish is the central focus of the background image. It is mounted on a complex metal support structure. The dish is pointed towards the upper left. The background is a hazy, light blue and white landscape, possibly a desert or a high-altitude site. The overall image has a soft, ethereal quality.

# **SITE SUMMARIES**



# Goldstone Campaign

## Atmospheric Phase Turbulence Studies



Goldstone, CA: Venus Site

Instrument : Two-Element Ka-Band Interferometer (20.2 GHz)

Data Collection Started : **May 2007**

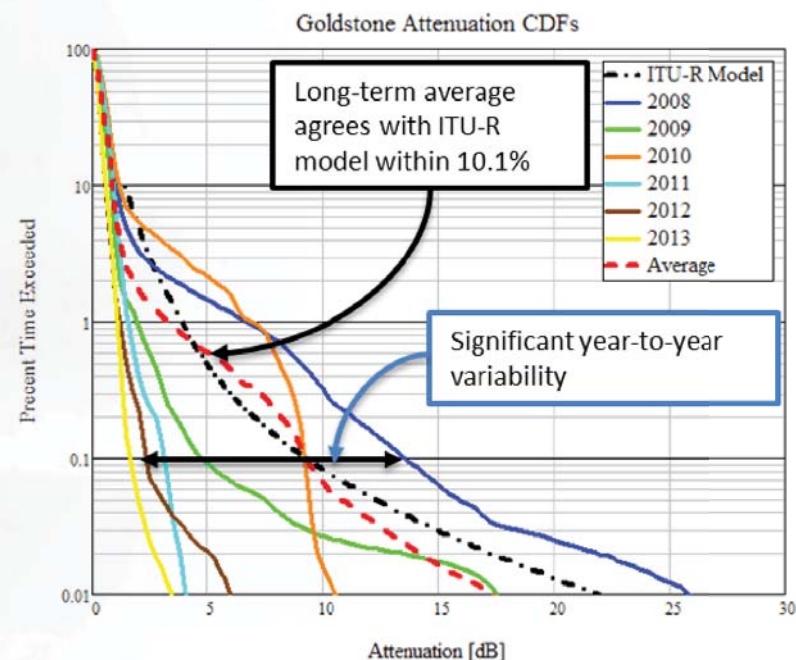
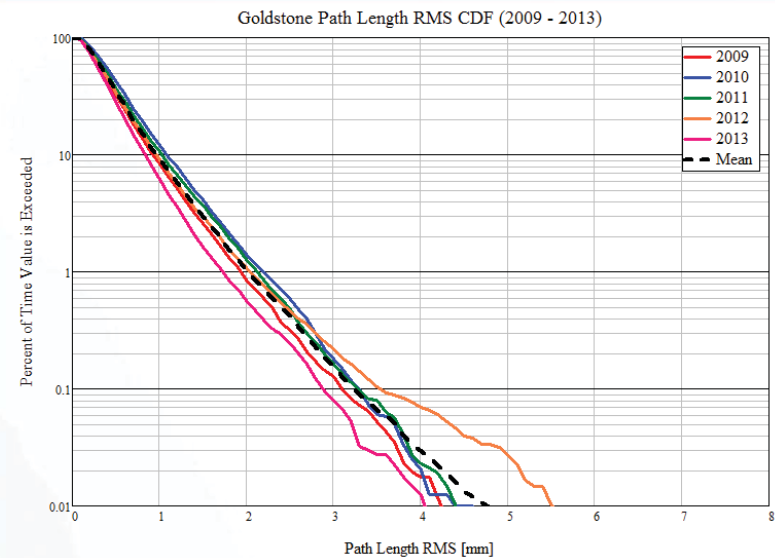
Data Collection Completed: **September 2012 (but ongoing)**

Total Number of Months : 88 (7.3 Years)

*Collected 7+ years of atmospheric attenuation measurements*

*Collected 7+ years of phase turbulence measurements*

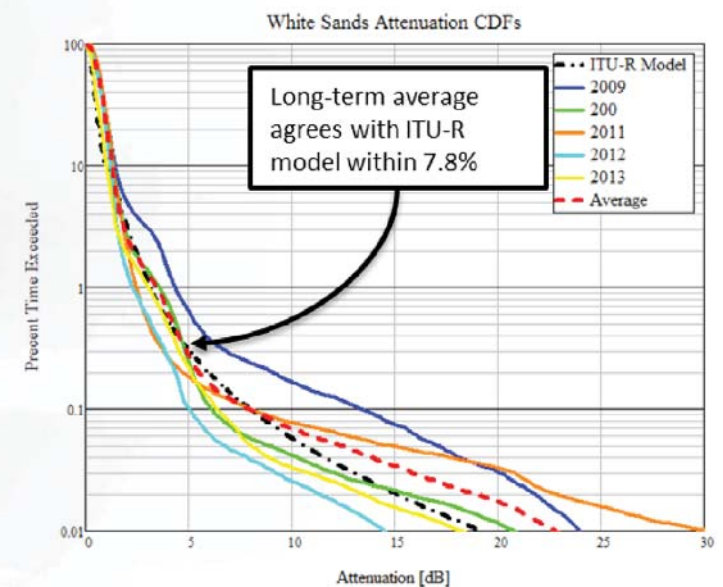
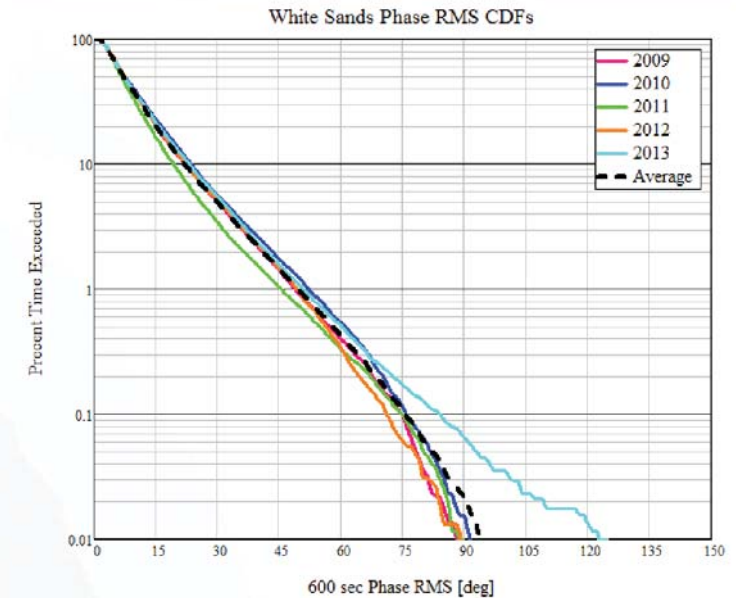
*Measurements have been validated with interferometer at secondary location at DSN Complex*





# White Sands Campaign

## Atmospheric Phase Turbulence Studies



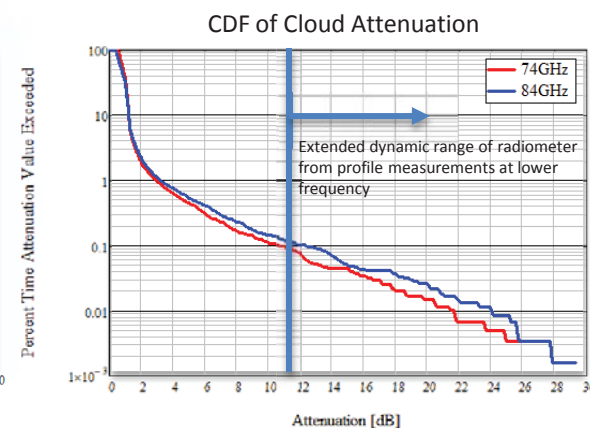
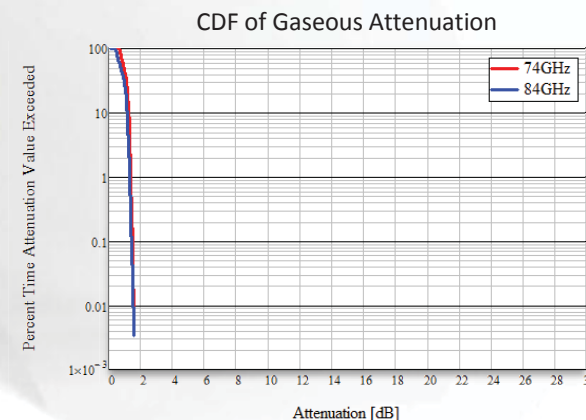
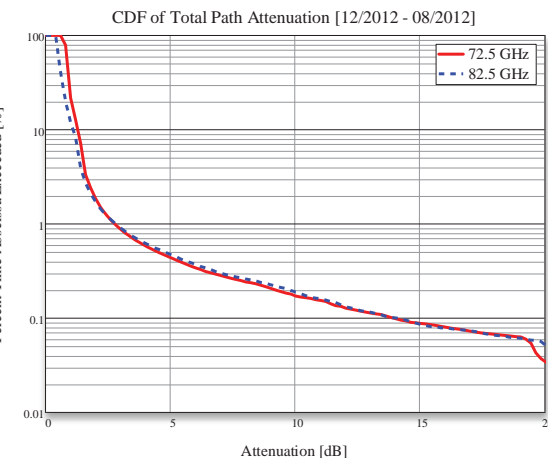
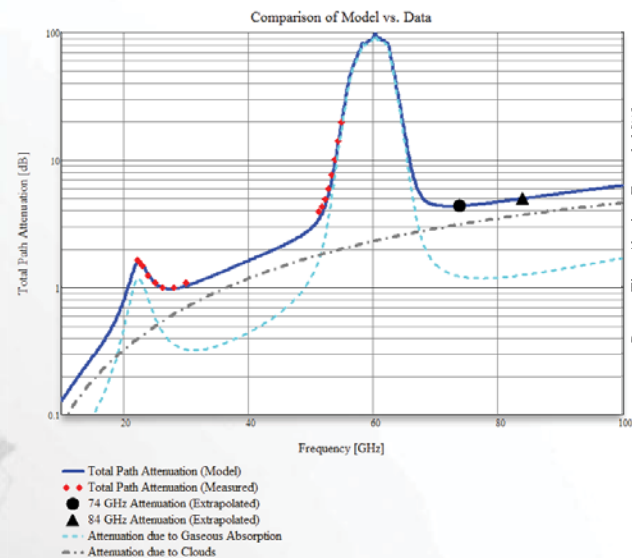
**Instruments :** Two-Element Ka-Band Interferometer (20.2 GHz)  
Microwave Profiling Radiometer (22-60 GHz)  
W/V-band Radiometer (82/72 GHz)

**Data Collection Started :** February 2009  
**Total Number of Months :** 68 (5.7 Years)

*Collected 5+ years of atmospheric attenuation measurements*  
*Collected 5+ years of phase turbulence measurements*

# White Sands Campaign

## Millimeter Wave Precursor Studies



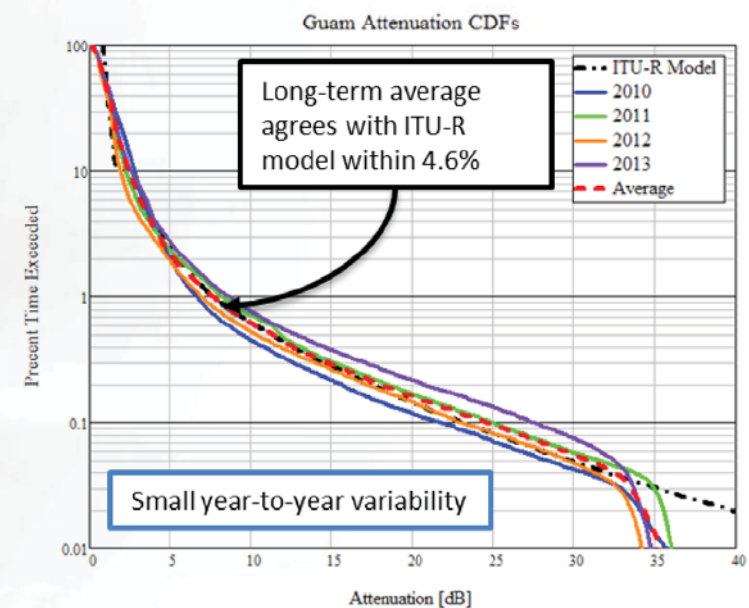
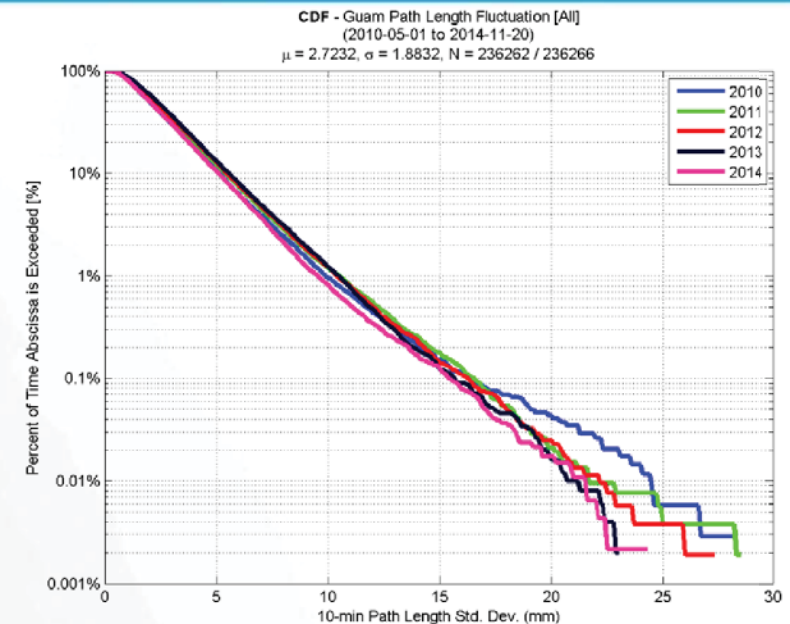
Instrument : Profiler, W/V-Band Radiometer  
 Data Collection Started : **December 2012**  
 Total Number of Months : 24 (2 years)

*Collected 2+ years of W/V-band gaseous and cloud attenuation measurements*  
*Extrapolation of profiler measurements/absorption models to W/V-band*  
*validated with direct W/V-band radiometer measurements*



# Guam Campaign

## Propagation Studies in the Tropics



**Instrument : Two-Element Ka-Band Interferometer (20.7 GHz)**  
**Data Collection Started : May 2010**  
**Total Number of Months : 54 (4.5 Years)**

*Collected 4+ years of atmospheric attenuation measurements*  
*Collected 4+ years of phase turbulence measurements*  
*Collected 4+ years of site diversity measurements*

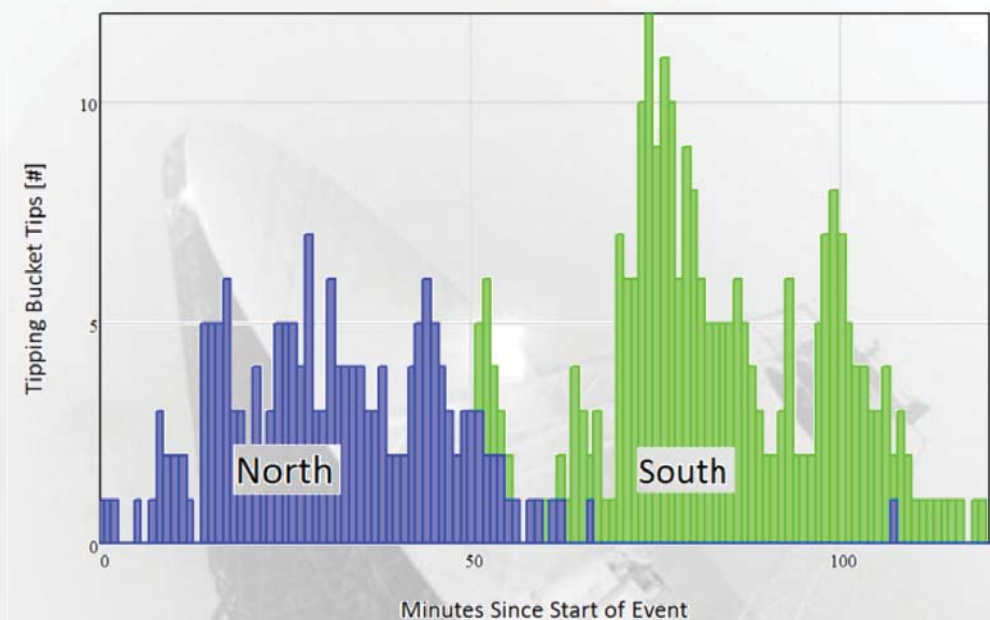


# Guam Campaign

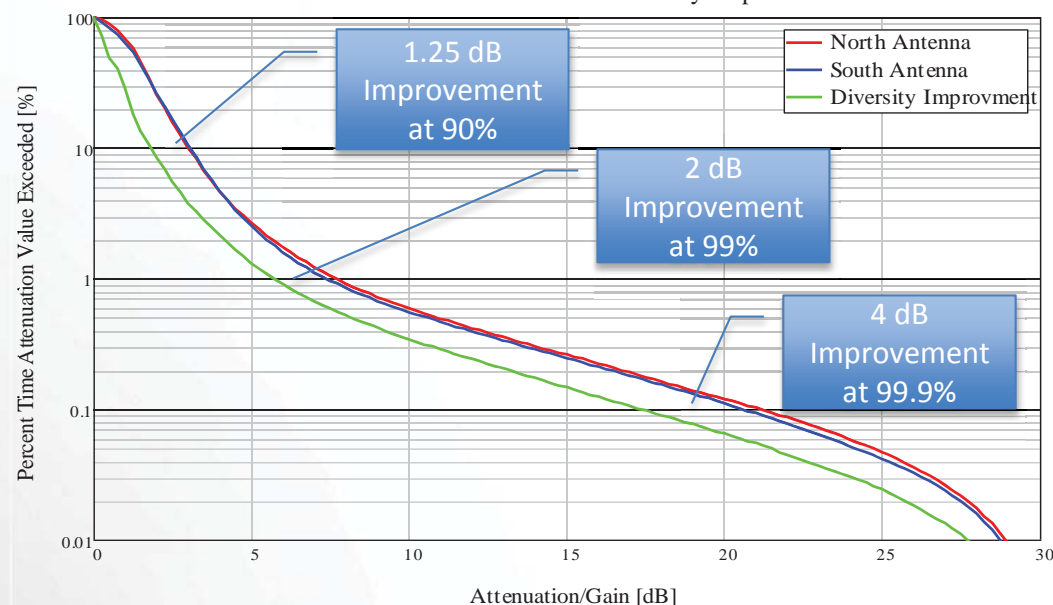
## Site Diversity Analysis



Example of Rain Diversity



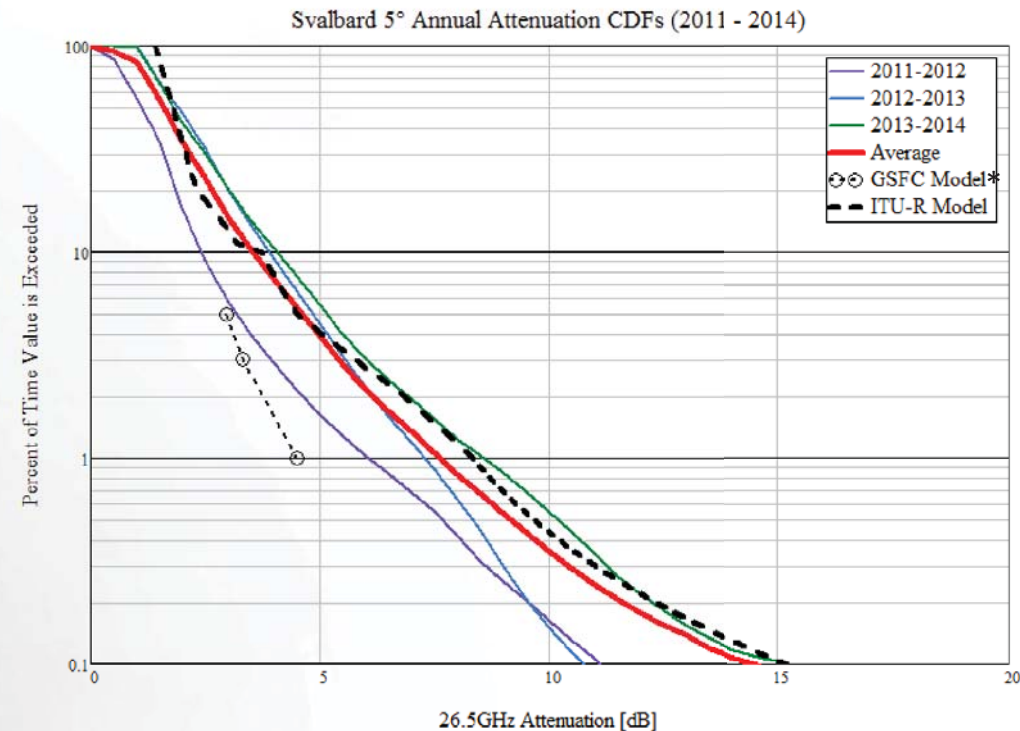
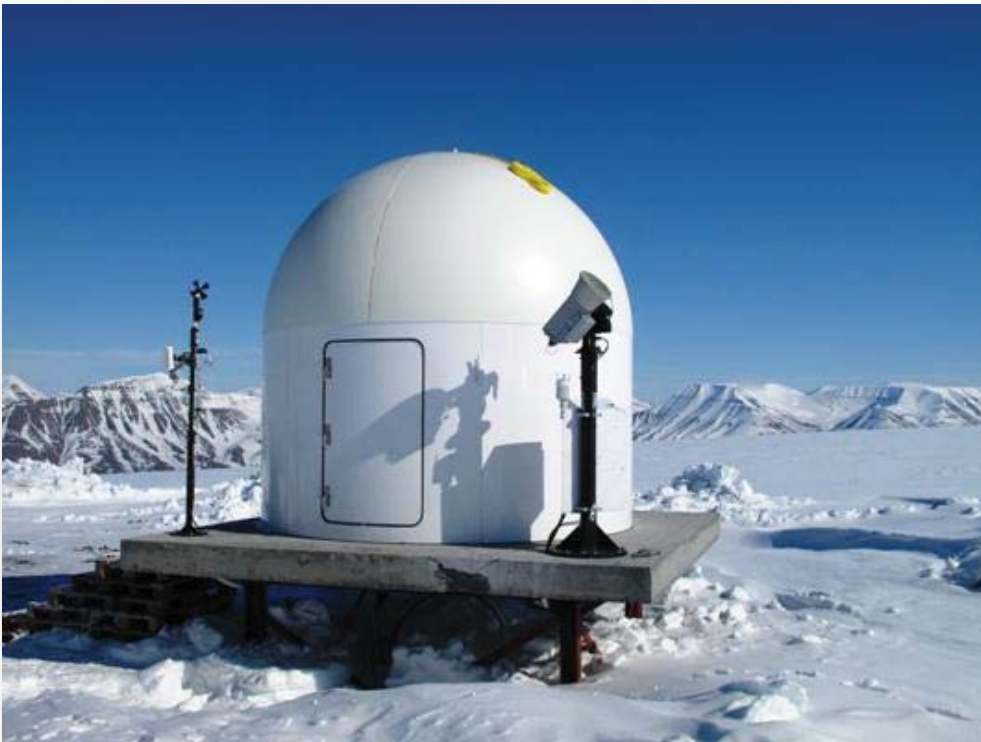
Guam 2010-2013 Attenuation and Diversity Improvement CDF's



- Compact, highly convective rainfall in Guam has shown evidence of rain diversity over short (600-m) antenna separation distances.
- Guam site diversity study indicates that meaningful diversity gain is possible within short baseline separation distances (<20 km) and is sufficient to overcome rain attenuation
- Analysis results lays foundation for modeling of short baseline site diversity, which his currently lacking
- **IMPACT: Conclude that high availability Ka-band operations in a tropical environment is possible utilizing short baseline site diversity**

# Svalbard Campaign

## Propagation Studies in the Polar Climate



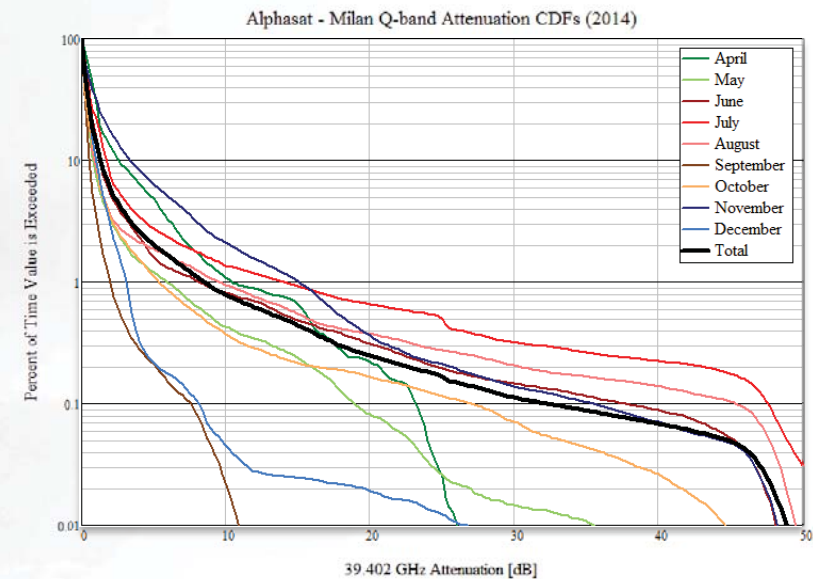
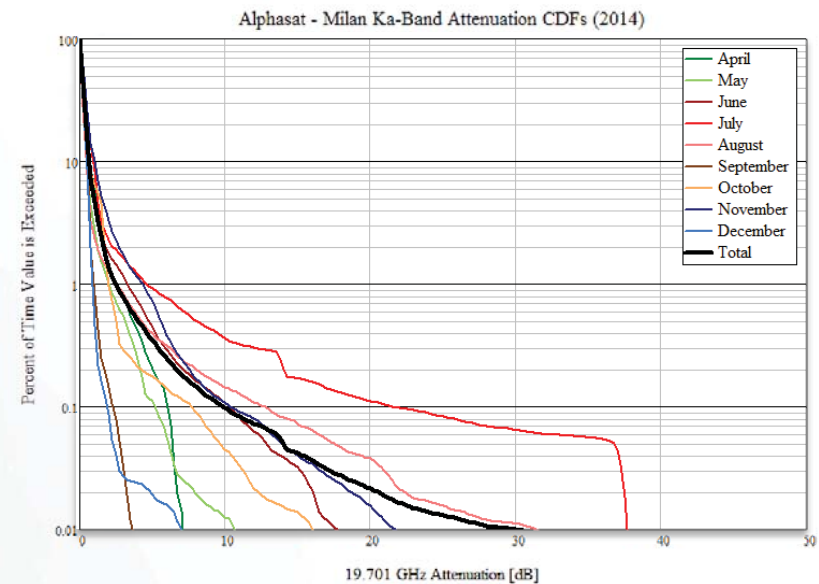
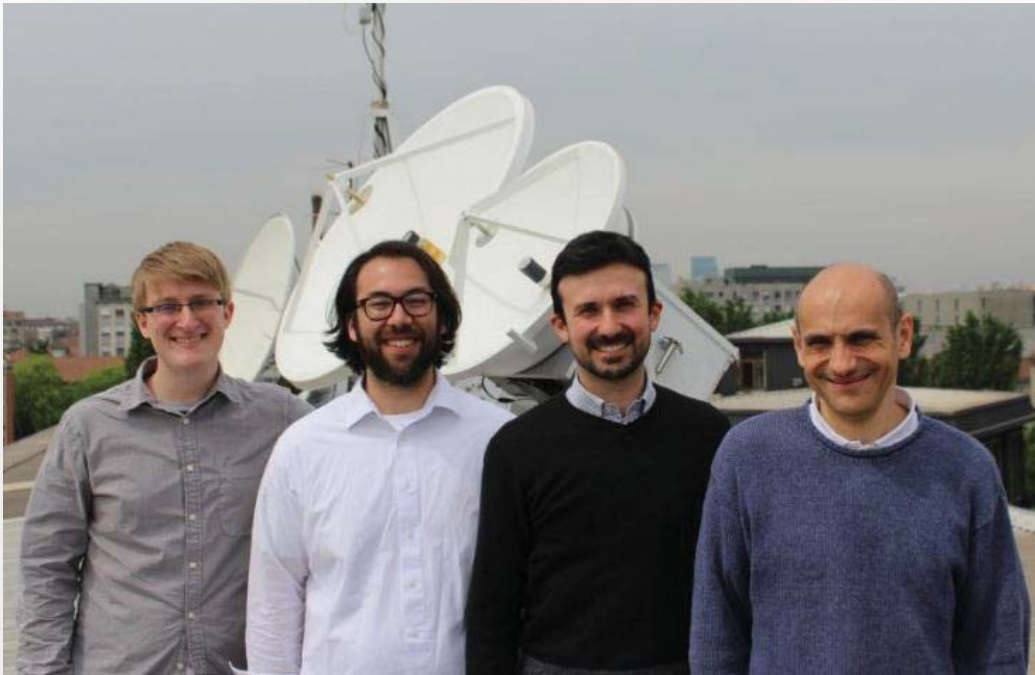
\* K. McCarthy, F. Stocklin, B. Geldzahler, D. Friedman, P. Celeste, "NASA's Evolution to Ka-band Space Communications for Near-Earth Spacecraft," AIAA SpaceOps 2010, Apr. 25-30, 2010, Huntsville, AL

**Instrument : Ka-Band Radiometer (26.5 GHz)**  
**Data Collection Started : May 2011**  
**Total Number of Months : 42 (3.5 Years)**

*Collected 3+ years of low elevation angle gaseous absorption*  
*Coordinating with ESA to install Ka-band (20.2 GHz) beacon*  
*receiver for rain attenuation/scintillation measurements*

# Alphasat Campaign

## Propagation Studies in the Q-band



**Instrument : K/Q-band Beacon Receiver (20/40 GHz)**  
**Optical Disdrometer**

**Data Collection Started : May 2014**

**Total Number of Months : 7 (0.6 Years)**

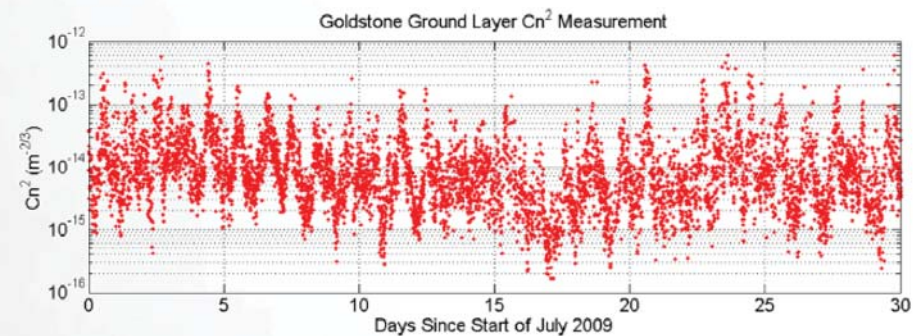
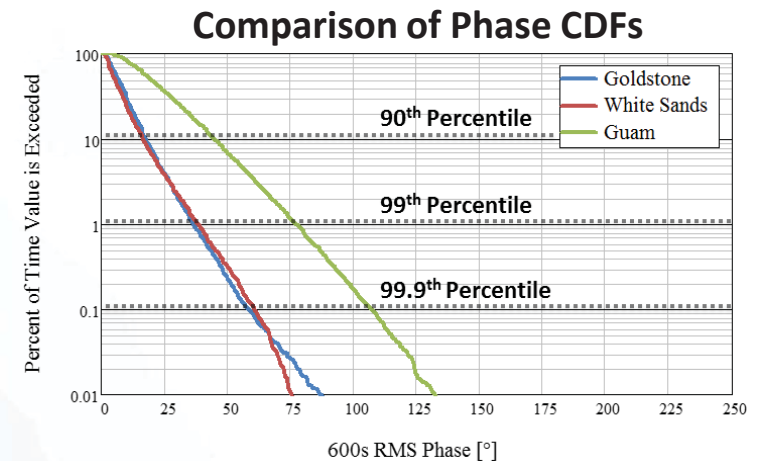
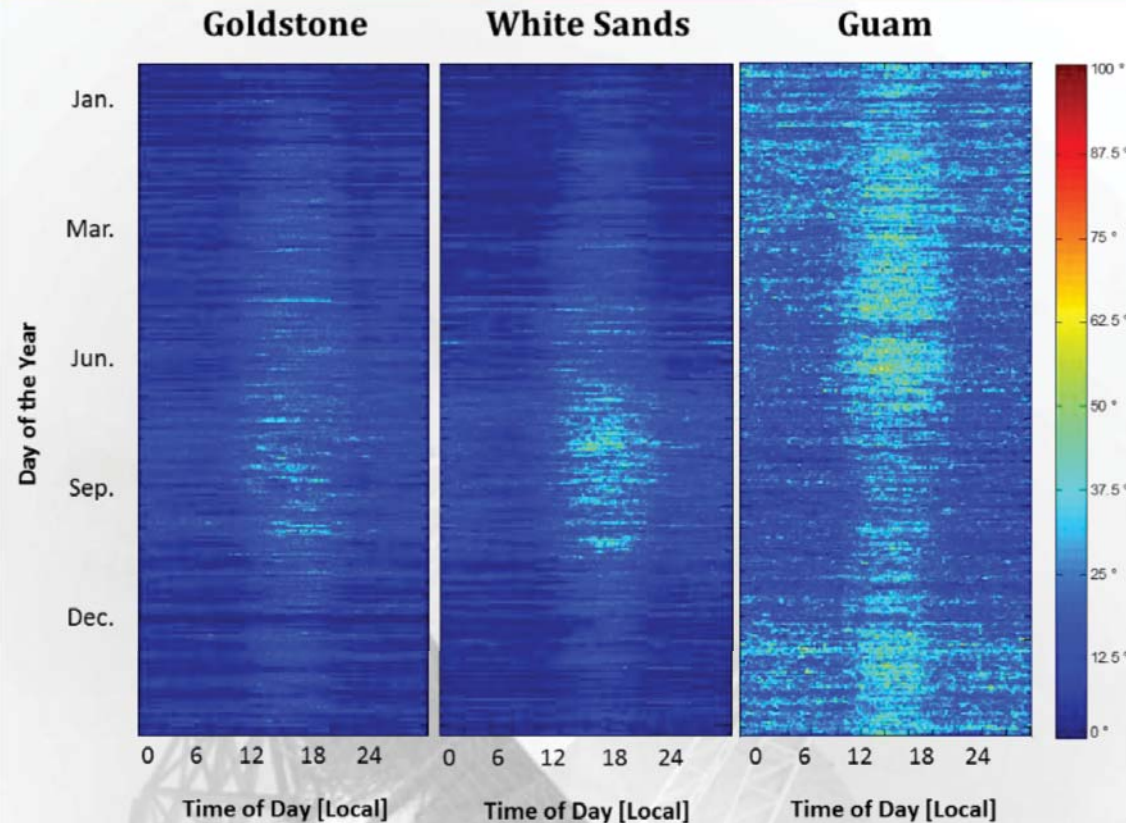
- First 40 GHz propagation data collected by NASA
- GRC receiver recognized as highest-performing receiver of all Alphasat experimenters (>40 dB dynamic range)
- Collaboration with ASI for 20km site diversity measurements



The background of the slide is a faded, grayscale image of a large radio telescope dish. The dish is parabolic and mounted on a complex metal support structure. It is angled upwards and to the left. The background is a light blue gradient with some faint, abstract shapes. The text "MODEL DEVELOPMENT" is overlaid on the lower left portion of the dish.

# MODEL DEVELOPMENT

# Atmospheric Microwave Phase Turbulence Modeling



Model for Phase Turbulence Statistics (TBD):

$$\sigma_\phi = f(Nwet, v, \theta, v)$$

Derivation of  $C_n^2$  from Interferometric Measurements:

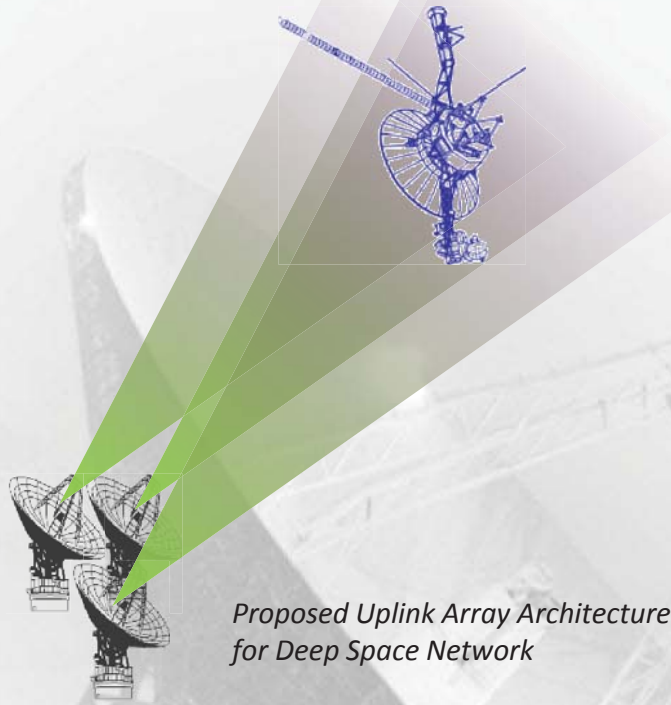
$$C_n^2 = 0.043 D_{\Delta H}(\infty) \Lambda_1^{-1} d^{-\beta} H^{-1}$$

TABLE II  
MEAN VALUES OF  $C_n^2$  AT NASA GROUND SITES

Location	$C_n^2$ [2010-2012]	$C_n^2$ [June-Aug.]	$C_n^2$ [Dec.-Feb.]	$C_n^2$ 99%
Goldstone, CA (DSN)	$2.04 \times 10^{-14}$	$3.02 \times 10^{-14}$	$8.45 \times 10^{-15}$	$1.55 \times 10^{-14}$
White Sands, NM (SN)	$2.08 \times 10^{-14}$	$4.40 \times 10^{-14}$	$5.99 \times 10^{-15}$	$2.85 \times 10^{-14}$
Guam (SN)	$9.8 \times 10^{-13}$	$8.7 \times 10^{-13}$	$1.1 \times 10^{-12}$	$8.3 \times 10^{-13}$

# Atmospheric Phase Turbulence in an Array Environment

## Deep Space Network (DSN)



*Proposed Uplink Array Architecture  
for Deep Space Network*

### Concept

Arraying of several small aperture antennas vs. single large aperture antenna provides the following advantages:

- Reduced maintenance costs
- Graceful degradation of performance of communications system
- Relative ease of meeting strict surface accuracy requirements for small apertures
- Enable new communications capabilities
- $N^2$  improvement in Effective Isotropic Radiated Power (EIRP)

$$EIRP_{array} = \sum_{m=1}^N G_m \cdot \sum_{n=1}^N P_n$$

Assuming identical antenna elements,

$$EIRP_{array} = G_{array} \cdot NP_0$$

$$\langle G_{array} \rangle = \eta D_0 \frac{1}{N} \sum_{m=1}^N \sum_{n=1}^N e^{-\frac{\sigma_{mn}^2}{2}}$$

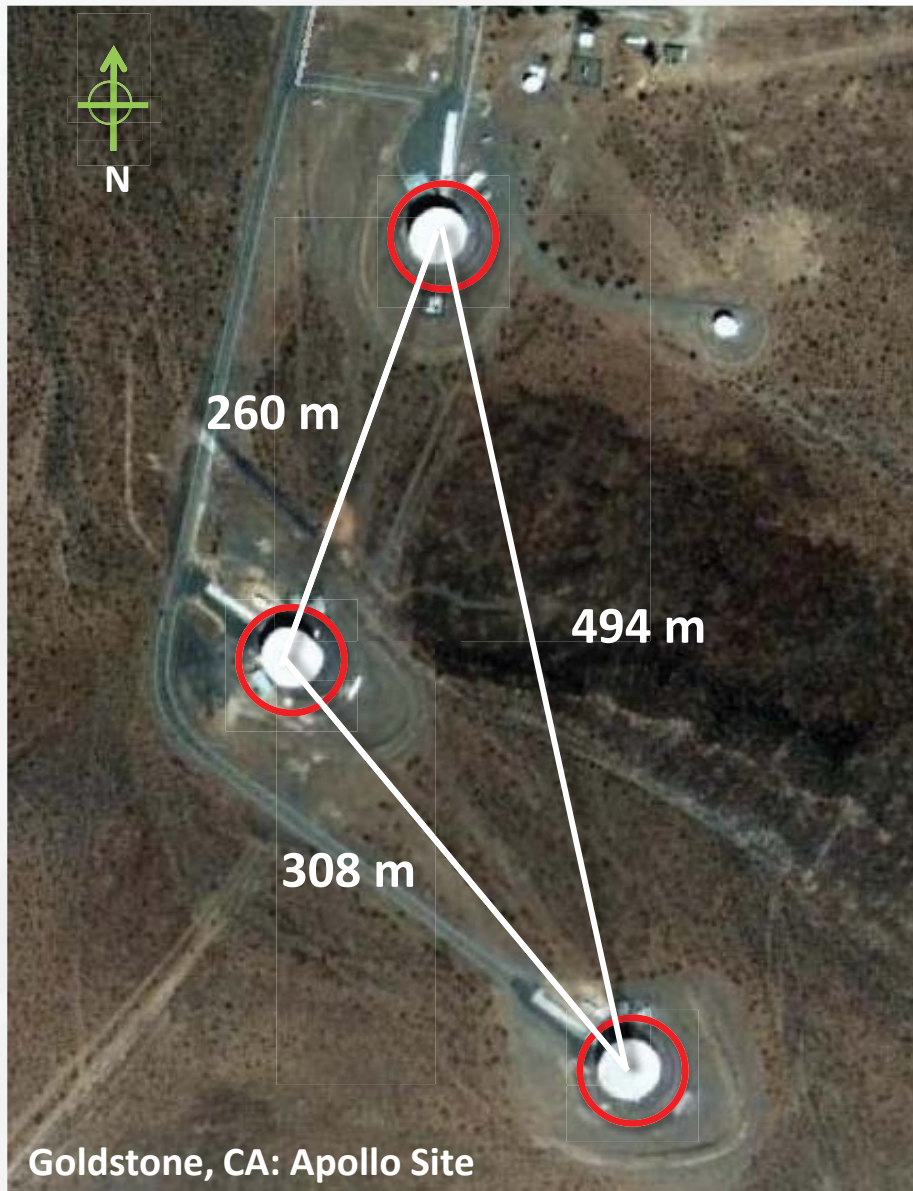
Propagation data characterizes this value  
(variance in phase amongst widely  
distributed antenna elements)

$$\sigma_{mn}^2(\theta_{el}, f, r) = \sigma_{mn}^2(\theta_0, f_0, r_0) \left( \frac{f}{f_0} \right) \left( \frac{r}{r_0} \right)^\alpha \left( \frac{\sin \theta_0}{\sin \theta_{el}} \right)$$

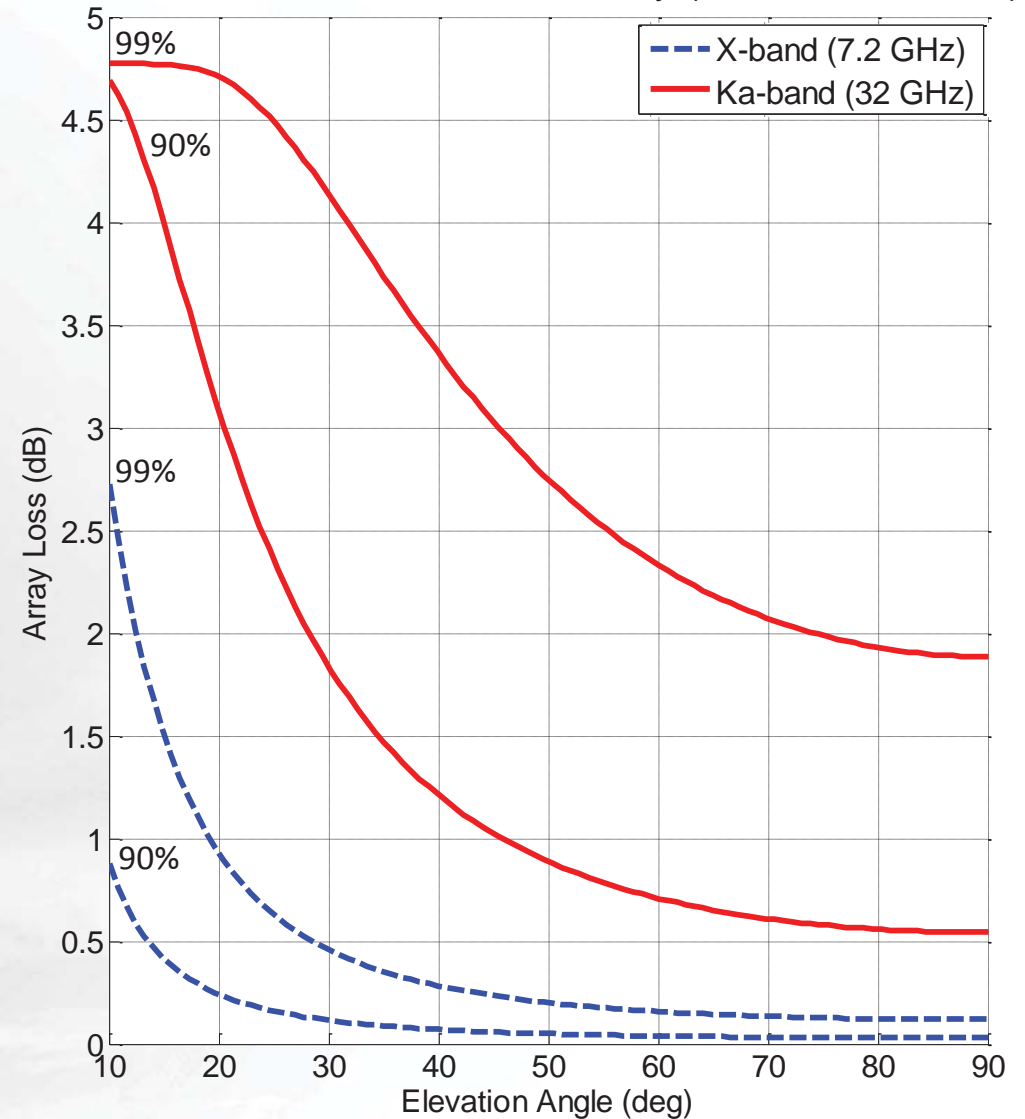


# Atmospheric Phase Turbulence in an Array Environment

## Deep Space Network (DSN)



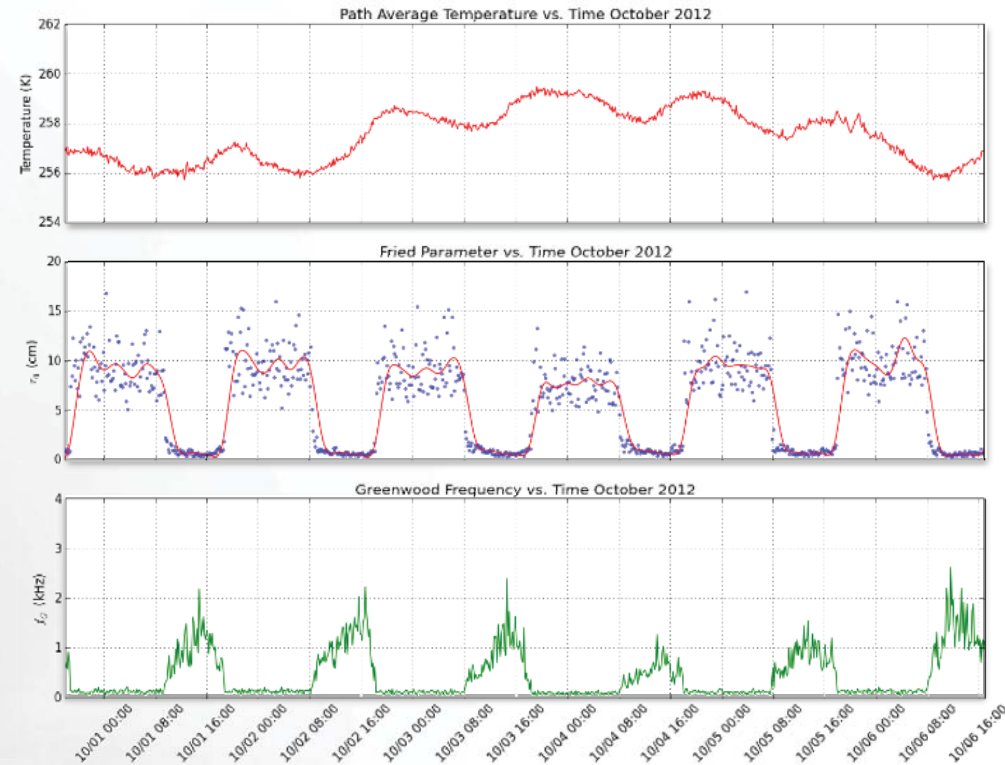
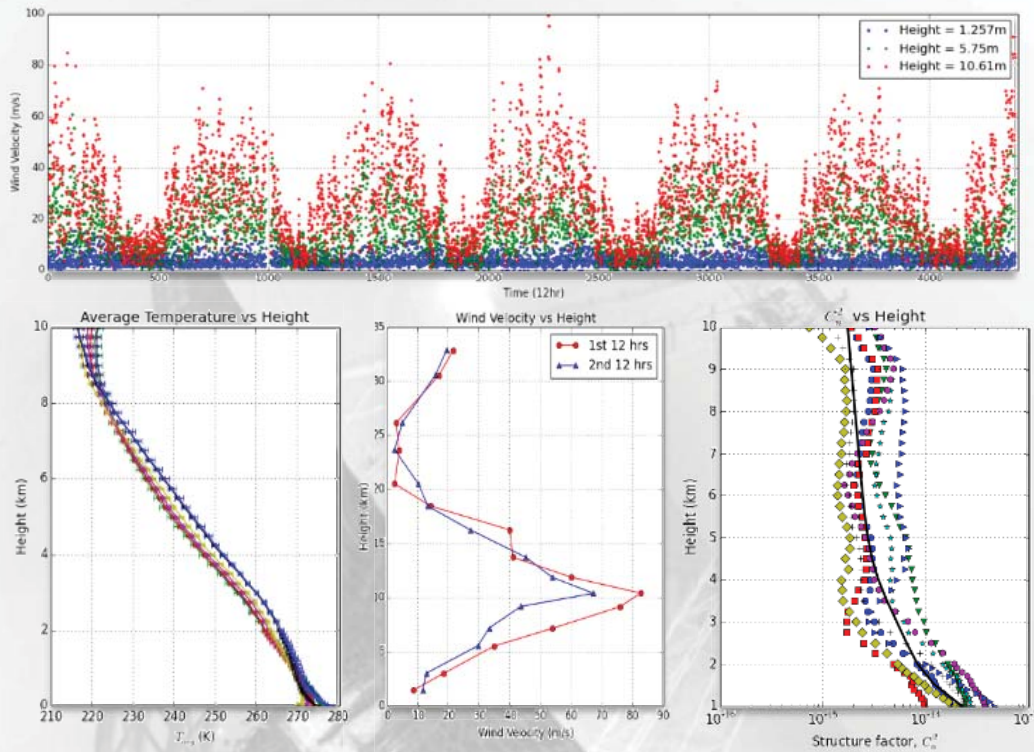
Array Loss at Goldstone due to Atmospheric Phase Noise: 90%-99% Availability (10 min timescales)



# Atmospheric Optical Scintillation Modeling



## Preliminary Analysis of Optical Performance at White Sands



### Modified Structure Parameters:

$$HV(h) = Ae^{-\frac{h}{H_A}} + Be^{-\frac{h}{H_B}} + Ch^{10}e^{-\frac{h}{H_C}} + De^{-\frac{(h-H_D)^2}{2d^2}}$$

$$\text{Coherence radius, } r_0 = 0.423 \left( \frac{2\pi}{\lambda} \right)^2 \int C_n^2(h) dh, \lambda = 1550\text{nm}$$

$$C_T^2(T, U, \Delta t) = \frac{4\langle (T(r) - T(r + U\Delta t))^2 \rangle}{k_U^{-2/3} \left[ 0.57722 + \log(U\Delta t) + \frac{3}{2} \log(2k_U^{2/3}) + \frac{1}{2} \left( \frac{v}{U} \right)^2 \right]}$$

$$C_n^2 = \left( \frac{77.689 \langle P \rangle}{\langle T \rangle^2} \right)^2 C_T^2(T, U, \Delta t)$$



# Optical Link Budget Analysis Tool



File Excel Generate Version STK

Username: user1 Project Title: Mission 1 Date and Time: 12/2/2014 10:04:09 AM Button

### Transmitter

1.55E+3	Wavelength (nm)
13	Laser Avg Output Power (W)
208	Laser Peak Output Power (W)
12.2	Tx Aperture Diameter (cm)
-2	Tx Optical Losses (dB)
1E-6	Maximum Desired BER
0.8	Platform Angular Jitter (μrad)
11.438	Beam Divergence Angle (μrad)
107.864	Transmitter Aperture Gain (dB)
51.109	Divergence To Jitter Ratio
-0.084	Pointing Error Loss (dB)
-1.251	Pointing Power Penalty (dB)
115.668	EIRP of Optical Tx (dBW)

### Receiver

4.76E-12	Irradiance at Rcv Aperture (pW/m <sup>2</sup> )
1.18E+3	Rx Aperture Diameter (cm)
180	Rx Obscuration Diameter (cm)
-1.5	Rx Optical Losses (dB)
-1	Focal Plane Losses (dB)
0.153	Rx Obscuration Ratio
147.472	Rx Aperture Gain (dB)
144.252	Receiver Total Gain (dB)
-99.783	Optical Power into Rcv Aperture (dB)
89.139	Rcvd Avg Signal Power (dB-Ph/Sec)
85.16	Detected Avg Signal Power/Sec (dB-Ph/Sec)
-6.424	Detected Avg Signal Power/Slot (dB-Ph/Slot)

### Detector

APD	Detector Type
100	Gain
0.0028	Ionization Factor
2.28	Noise Figure
0.1	Filter Noise Bandwidth (nm)
0.4	Quantum Efficiency
-118.891	Rx Field of View (dB-sr)
300	Ambient Temp (K)
5E+4	Load Resistance (Ω)
1.294E+9	Detector Dark Noise
91.222	Total Detected Noise/Sec (dB-Ph/Sec)
-0.361	Total Detected Noise/Slot (dB-Ph/Slot)

### Signaling

180	Data Rate (Mbps)
16	PPM Mod Index
0	DPSK Bits/Symbol
0.5	FEC Rate
-1	Coding Performance Noise Loss (dB)
-0.5	Coding Performance Code Rate Loss (dB)
-0.5	Coding Distance From Capacity Loss (dB)
-0.7	Decoder Implementation Loss (dB)
0.694	Symbol Duration (ns)
2.607	Detected Signal (dB-Cts/Bit)
1.593	Required Signal (dB-Cts/Bit)
1.246	Log-Normal Channel Mean
0.095	Log-Normal Channel Variance

### Channel

1.192E+8	Range (km)
PPM	Modulation Type
Weak	Turbulence
0.1	Scintillation Index
-0.72	Atmospheric Attenuation (dB)
-359.703	Free Space Loss (dB)

### Link Performance Metrics

-0.649	Max Channel Capacity (dB-Bit/Ph)
-1.86	Channel Capacity w/ Noise (dB-Bit/Ph)
1.014	Link Margin w/o Coding (dB)
0.005	Uncoded BER for Free Space
0.011	Uncoded BER for Turbulence
-2.7	Coding Implementation Loss (dB)
2.917	Link Margin w/ Coding (dB)

### Background

0.009	Sky Irradiance (W/cm <sup>2</sup> /sr/μm)
0.007	Planetary Irradiance (W/cm <sup>2</sup> /sr/μm)
68.372	Detected Background Ph/Sec (dB-Ph/Sec)

Calculate!

- Rapid assessment of the operation of an optical communications link anywhere within the solar system as well as within GEO/LEO orbits
- Dynamic evaluation of optical link operation, accounting for the locations of deleterious noise sources with respect to the link and their impact on, e.g., achievable data rate during these periods
- Provides temporal and data rate connectivity throughout the lifetime of a mission yielding calculations for potential total data throughput of a mission
- Tool can be directly interfaced with the Satellite Tool Kit (STK) from which it gets its dynamic capability.
- Software configuration of tool allows extensive reporting capabilities as well as the flexibility to add as 'modules' new optical detector types, new modulations schemes, etc.
- Optical tool can be employed for the simulation of entire relay satellite system when used with an attendant tool for RF.



The background of the slide is a faded, grayscale image of a large radio telescope dish, likely the Arecibo radio telescope, situated in a mountainous landscape. The dish is the central focus, with its complex support structure visible. The text "PROPAGATION LABORATORIES" is overlaid on this image in a large, bold, black font.

# **PROPAGATION LABORATORIES**

# RF Propagation Laboratory



Bldg. 55 Rooftop radiometer testing



Bldg. 55 Propagation Laboratory used for component/system level testing and integration



**Feed horn system upgrade completed to transition ground station for operation to Ka/Q/V/W bands**

NASA Ground Station (NGS) 5.5-m beam waveguide antenna for receiver system testing/check-out



# Millimeter Wave Laboratory



Bldg. 55 Millimeter Wave Laboratory for component/system level testing and integration

Presently transitioning test equipment to millimeter wave:

- Spectrum Analyzer  
(up to 90 GHz)
- Vector Network Analyzer  
(up to 110 GHz)
- Laboratory Investment Fund proposal in place to procure Signal Generator  
(up to 110 GHz)

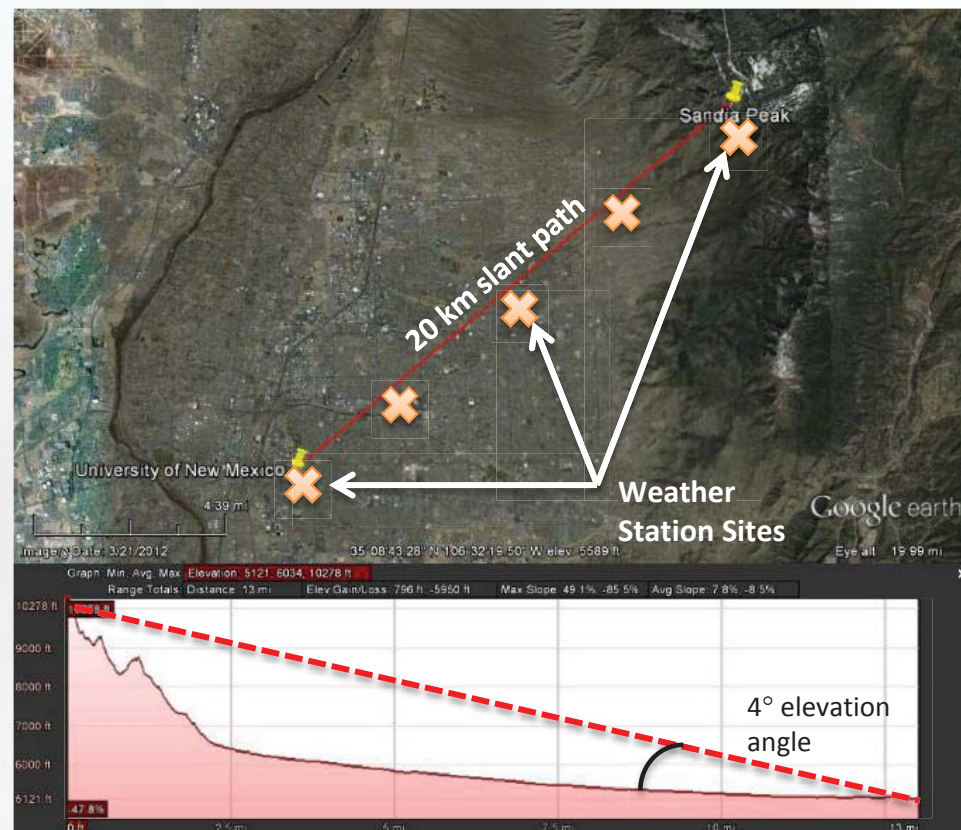


# FUTURE PLANS

*Activities in the Millimeter Wave*

# AFRL Terrestrial Link Experiment (Summer 2015)

## Propagation Models/Measurements in the V/W-band



*Collaboration with AFRL and University of New Mexico (UNM) provides cost-effective opportunity to conduct immediate near-term rain fade and depolarization measurements prior to having an active W/V-band beacon for model validation and rain fade mitigation.*

Measurement equipment to include:

- Beacon Transmitter on Sandia Peak (72/84 GHz)
- Beacon Receiver at UNM
- V/W-band Microwave Radiometer at UNM
- *Optical Transmitter/Receiver for concomitant measurements along path*
- Multiple Optical Disdrometers along path for rain drop size distribution measurements
- Multiple weather stations along path for path profiling information
- Super Doppler Radar for path profiling information

### IMPACT:

- **Terrestrial Line-of-Sight Experiment in W/V-band will provide immediate preliminary validation/prediction of mm-wave rain attenuation and depolarization models prior to the expected W/V-band beacon payload launch in 2018 timeframe.**
- **Will provide a testbed for prototype propagation terminals to reduce experiment risk.**

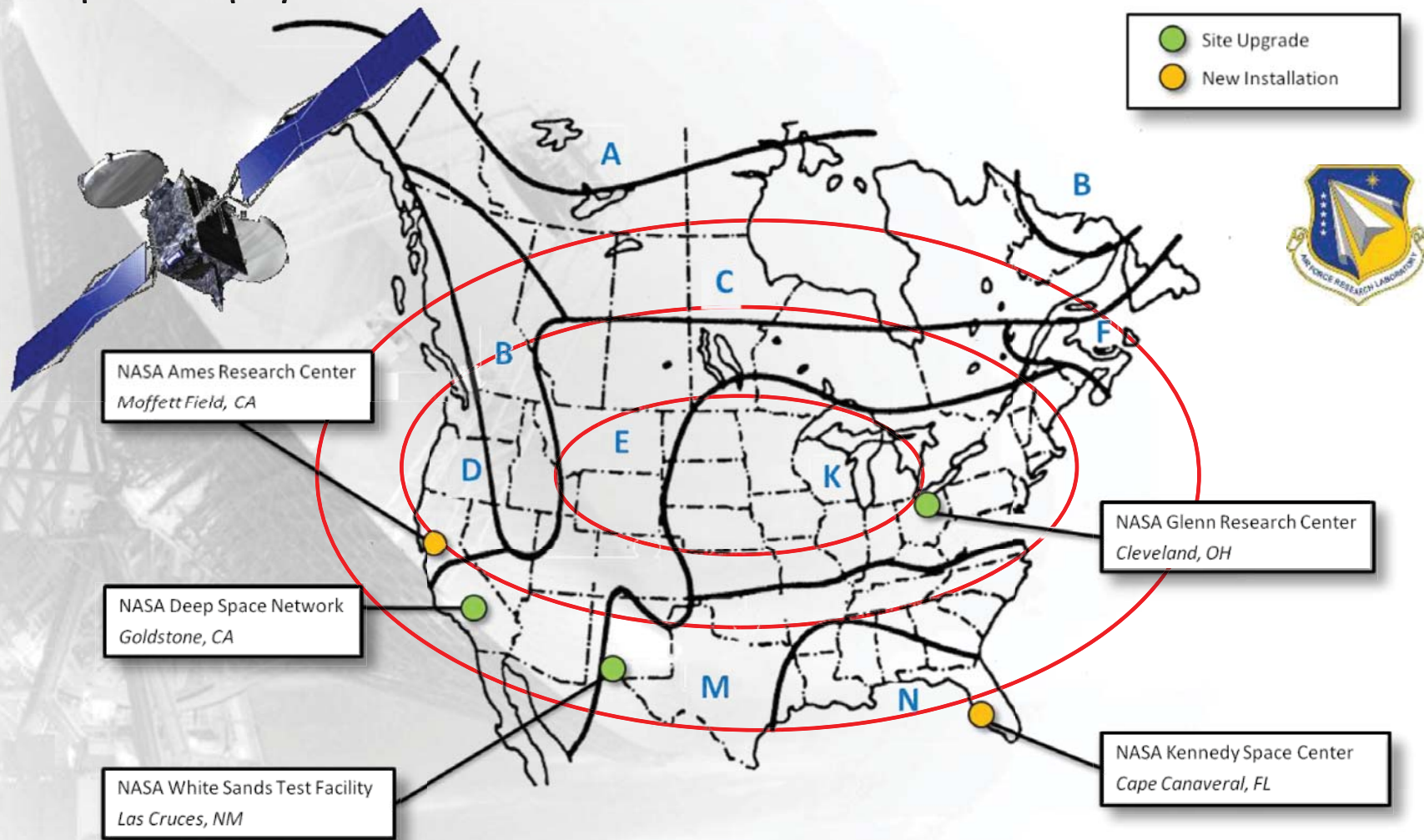


# W/V-band Satellite Communications Experiment

## Opening the Millimeter Wave



- AFRL W/V-band Satellite Communications Experiment (WSCE)
  - Conduct ACTS-like CONUS propagation campaign at V/W bands
  - Expected payload launch date in 2018



A large, white, parabolic radio telescope dish is the central focus of the background image. It is mounted on a complex metal support structure. The dish is angled upwards and to the left. The background is a soft-focus landscape with rolling hills under a bright, hazy sky. The overall image has a light, airy feel with a blue and white color palette.

**THANK YOU!**

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